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The U.S. Army Research Laboratory's Auditory Research for the Dismounted Soldier: Present (2009–2011) and Future

by Tomasz R. Letowski, Angélique A. Scharine, Jeremy R. Gaston, Bruce E. Amrein, and Mark A. Ericson

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14. ABSTRACT

The objective of the U.S. Army Research Laboratory auditory research program is to enhance Soldier capabilities by understanding the principles that affect auditory perception, including interaction with military equipment, providing the Soldier with uncompromised auditory situation awareness, effective communications capabilities, and protected hearing. Research activities described in this report are centered on the auditory spatial orientation capabilities needed by the dismounted Soldier for navigation in a complex acoustical environment that includes noise, movement, reverberation, and unpredictability. In this environment, the Soldier must communicate both face-to-face and over a radio; detect, identify, and localize ambient (non-speech) sound events; and be protected against impulse and steady-state acoustic threats. This has led to research into the effects of various types of headgear on directional sound detection, auditory localization, and auditory distance perception. One goal of the program is to develop a comprehensive model of localization and distance estimation that incorporates the acoustic features of the Soldier environment for future use in equipment evaluation. Another goal is to develop methods of auditory training that improves a Soldier’s ability to differentiate and recognize various sound sources. The unique capabilities of the new Environment for Auditory Research facility permit us to take this research to the next level.

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Summary

The U.S. Army Research Laboratory (ARL) conducts, as a part of its overall research program, basic auditory research that enables dismounted Soldiers to have sufficient hearing capability to efficiently and effectively carry out their missions while remaining safe. The Soldiers need to maintain sufficient auditory situation awareness (ASA) to detect, identify, and localize acoustic events while at the same time being sufficiently protected from the hazards in their environment due to unsafe levels of noise and ballistic threats.

The purpose of the ARL auditory research program is to address issues in Soldier performance resulting from military tasks and existing Soldier systems; however, the executed studies are designed to emphasize discovery of underlying general phenomena and mechanisms rather than to deal only with specific Soldier systems. The data gathering, simulations, and models developed by ARL auditory researchers are focused on providing general guidance to Soldiers, commanders, and system developers to make Soldiers more effective and safe rather than improving or modifying existing pieces of equipment. Some examples of research topics related to these goals are

- developing effective auditory training methods,
- improving Soldier auditory sensitivity and communication ability on the battlefield,
- quantifying the effects of ear coverage (helmets and hearing protection) on sound localization,
- assessing the effects of linear and nonlinear hearing protection devices on speech recognition and ASA, and
- identifying the auditory limits created by various operational conditions.

In conducting their research, ARL researchers are focused on tying specific auditory capabilities to Soldiers' mission requirements. As data on auditory spatial performance are accumulated, they are tied to specific patterns of the head-related transfer function and constitute the basis for the development of the spatial perception model. The objective of the modeling effort is to account for the effects of changes in acoustic environment on ASA. The model is intended to aid in the development of personal protective equipment that minimally impairs ASA and in quantifying the audibility of acoustic signatures of both stationary and moving objects. Further, an auditory model of spatial perception can be incorporated into general models of Soldier performance, allowing a direct connection between auditory capabilities and Soldier mission success.

The main research tool used in the conduct of auditory research studies is the Environment for Auditory Research (EAR). Auditory spatial perception research requires research facilities that are both acoustically well controlled and adaptable. The EAR was developed with these research requirements in mind. In all spaces there is practically no unwanted noise and minimal or controlled reverberation. The spaces were designed to facilitate the creation of a variety of listening environments and to enable comparisons of indoor and outdoor listening environments. These spaces have various shapes and volumes and are well instrumented, making them uniquely suitable for the simulation of various auditory environments encountered by dismounted Soldiers. The unique features of EAR position ARL auditory researchers to make significant contributions to the understanding of auditory perception, especially auditory spatial perception.

1. Purpose

The primary research group carrying on auditory research at the U.S. Army Research Laboratory (ARL) is the Auditory Research Team (ART) at the Human Research and Engineering Directorate's (HRED's) Perceptual Sciences Branch. The main research goal of ART is to determine conditions providing the dismounted Soldier with optimal auditory situation awareness (ASA) and to define the role of audition in multisensory perception and communication. Specifically, this research addresses Soldiers' ability to detect, identify, and localize sound sources; communicate and network through spoken messages; and use auditory symbology in tactical displays and warning signals designs.

This report describes research addressing the auditory needs of the dismounted Soldier with emphasis on spatial perception and how research addressing those needs differs from traditional laboratory research. Although ART's research extends to other topics, such as communication interfaces, speech communication in adverse environments, and auditory displays and related auditory symbology, they are subordinate to auditory spatial research and are not discussed in detail in this report. Further, while ARL-HRED is just one of a number of Department of Defense (DOD) research laboratories, its role is to fulfill the unique gap in research conducted in DOD by being the center of DOD auditory research for the dismounted Soldier. This role will be described in the context of past and ongoing research, as well as planned research. More importantly, this report presents how conducted research activities embody ARL's vision of providing basic research that enables the dismounted Soldier to increase efficiency, operate safely, and improve mission success.

2. ARL-HRED's Auditory Research Role

ARL auditory research is unique by design and intended to address dismounted Soldier–related research gaps that are not addressed by academia, industry, or other DOD agencies. The conducted research is a combination of efforts that are classified as budget categories 6.1 and 6.2. In order for the research studies to be considered as budget category 6.1 (basic research), they must directly seek to identify principles that can be generally applied to any situation or in any context. Budget category 6.2 (applied research) refers to work that extends this research toward early development and evaluation of particular devices and equipment. Research studies described in this report are predominantly 6.1 studies. However, because of the specific mission of ARL-HRED in supporting the Soldier, ART's basic research studies are oriented less toward theoretical understanding of hearing principles than on how auditory capabilities impact general Soldier functioning in the larger context of mission performance. These research questions are

derived from the Soldier capability gaps identified by the U.S. Army Training and Doctrine Command (TRADOC), Soldier debriefings, and from questions that have arisen during evaluations of prototype devices and Soldier systems.

As just described, audition-related Army research conducted at ARL-HRED fulfills a unique knowledge gap in the context of research activities of academia, industry, or other services. However, ART is not the only research group in the DOD dealing with auditory perception; it uses various formal and informal means to cooperate and share results with other laboratories in the Army (U.S. Army Aeromedical Research Laboratory [USAARL], Walter Reed National Military Medical Center [WRNMMC]) and in the other services (Naval Submarine Medical Research Laboratory [NMSRL], Air Force Research Laboratory [AFRL]) involved in hearing research. The mission of USAARL and WRNMMC is to conduct research toward the medical fitness for duty of the Soldier with the result that hearing research is often geared toward the effects of hearing loss and noise on detecting and recognizing speech. AFRL conducts research on speech communications and spatial auditory displays for airborne and control and communications environments.

There is reasonable potential for some overlap in the research conducted by ARL and the other DOD laboratories; however, ART's focus is on dismounted Soldiers and the issues they face. In addition, ART and other research groups have formed a DOD-wide Auditory Research Working Group that includes all the laboratories mentioned previously as well as the Department of Veterans Affairs, which serves as an information exchange and research coordination platform. Therefore, the actual overlap is minimal. In addition, ART has broad ties with academia and industry that allow ARL to leverage audition-related research conducted outside of DOD.

3. ARL-HRED's Auditory Research Facilities

The research infrastructure available at ARL-HRED includes a unique world-class multispace auditory spatial perception laboratory, the Environment for Auditory Research (EAR), several smaller laboratory spaces suitable for hearing testing, head-related transfer function (HRTF) measurements, bone conduction and tactile perception studies, and signal processing. The EAR consists of four research spaces—Sphere Room, Dome Room, Distance Hall, and Listening Laboratory—and is physically coupled with the OpenEAR, an adjacent open space suitable for field research. A detailed description of EAR and its operational capabilities is included in appendix A of this report. Field studies requiring a larger open area are conducted at the Electromagnetic Range on Spesutie Island (e.g., auditory distance estimation up to 1000 m), M Range Shooter Performance Facility (e.g., localization of distant weapon fire), Mobility-Portability Course at KD Range (e.g., auditory performance during clearing physical obstacles), or at the Cross-Country Course (e.g., auditory performance during movement). All these facilities are ARL assets located at Aberdeen Proving Ground, MD.

Although the theoretical principles that guide much of current human understanding about auditory spatial orientation come from academic research, there are unique features of the Soldier environment that guide ART's research questions. For example, the spatial scale of Soldier operations differs significantly from that of daily experiences of most civilians, which are addressed in academic research.

Furthermore, Soldiers' environments are less predictable, less familiar, and far more dangerous; all these factors affect the Soldier's response to auditory stimuli. Like many industrial environments, there are unsafe noise levels, but unlike them, the consequences of being unable to hear, identify, and locate are more severe. Last, the target population—Soldiers—is less uniform (regarding age, experience, state of hearing, level of education, etc.) than populations investigated in most academic studies. Therefore, while it is still important to isolate variables of interest in order to understand their function, it is also important to understand the general effects of acoustic complexity, time and stress factors, the Soldier's mission, and the effects of interaction of audition with other modalities on the Soldier's performance.

4. Critical Auditory Issues for the Dismounted Soldier

Soldiers use auditory information to alert them to threats, survive danger, and effectively complete their mission in urban and low-visibility environments. Availability of auditory information on the battlespace is especially critical because Soldiers operate in environments that are dynamic, unpredictable, and lethal. There is no "typical" battlespace environment, and there are often dramatic differences among operational acoustic conditions. For example, the relative quiet of the rural countryside is in sharp contrast to the bustling, pulsing noise of a city. Moreover, these acoustic conditions continuously change in time. Rather, a calm, even monotonous environment can be abruptly and dramatically changed without warning by the gunfire of an ambush. Whether the sounds of gunfire interrupting the relative quiet of the countryside, or a sudden reduction in typical city noise, a change in the soundscape serves as an alerting system for the Soldier. Indeed, informative sounds can be heard from any direction, in visually opaque environments, and around intervening structures, and they often act as an early warning and a coarse guiding system for vision. Important sound sources can include both diffuse and discrete sound sources that, in turn, can provide meaningful information about environmental changes as well as the acoustic signatures of enemy and friendly forces. The ability to rapidly develop a conceptual map of the relevant acoustic features in the Soldier's surroundings has a crucial impact on his survivability and mission success and critically depends on auditory information.

4.1 Auditory Situation Awareness (ASA)

The detection and subsequent recognition and localization of sounds in operational environments are hampered by ambient noise, hearing loss, and the use of personal protective equipment (PPE), such as helmets, and hearing protection devices (HPDs). Helmets are indispensible systems in most military operations, protecting the Soldier's head against ballistic and fragmentation threats. In addition, respiratory masks and hoods must be used when needed. Similarly, HPDs need to protect the Soldier's hearing in various military missions since the intensity levels of noise from vehicles, aircraft, and weapons fire are in a range that can damage both short- and long-term hearing sensitivity. Thus, a Soldier's head and hearing need to be protected, but the use of neither helmets nor hearing protection should degrade ASA or the Soldier's ability to communicate. Wearing head and hearing protection potentially changes the Soldier's sensitivity to his auditory environment and can negatively impact ASA especially when it is needed the most. Wearing HPDs in low-level noise also affects the Soldier's ability to communicate. However, not wearing hearing protection leaves the Soldier vulnerable to temporary (temporary threshold shifts) and permanent (permanent threshold shifts) hearing loss. This dilemma exemplifies the problem of noncompliance with requirements regarding hearing protection and the resulting high rate of service-related hearing loss.

A Soldier's tasks, especially those of a dismounted Soldier, are potentially dangerous, regardless of the actual acoustic environment. Detecting auditorily perceived threats, whether in quiet or in noise, is critical for survivability on the battlefield. Any degradation in the Soldiers' hearing ability due to equipment located near the ears or because of a hearing loss reduces their detection and communication performance and consequently their reactions to the potential threat. Acoustic complexity is not unique to a Soldier's environment; however, the consequences of ambiguous auditory information are greater because of its dangers. Therefore, ARL-HRED's research studies include the effects of noise, reverberation, and other physical changes to the waveform on ASA. Rather than view acoustic complexity as simply degrading the signal, ART's research is geared toward the development of predictive models that incorporate these features. These models will also include the effects of human familiarization with and adaptation to the environment and to routine tasks.

Most people adapt quite quickly to surrounding environments—traveling routine routes, experiencing routine traffic, working with familiar people, doing familiar tasks. Sounds that occur in every-day environments are familiar, and our responses to those sounds are practiced. Soldiers may be operating in a novel environment that is very complex, or they may have the benefit of familiarity and learning that allows them to organize and simplify a complicated scene. One critical issue for ART's research is that most auditory studies reported in literature were conducted in a reduced context and over a very limited duration. Therefore, ART's research needs to build from understanding how to translate the knowledge about auditory processing of a simple novel context to a complex environment where auditory processing interacts with prior experience and learning. How does ASA build over time? How does training interact with

experience? What are the effects of long-term (hours to days) exposure to a specific environment? What is the effect of memory and fatigue on auditory perception? How do natural operational conditions affect Soldier performance?

ART's EAR infrastructure (see appendix A) was designed and built in response to the need to create large reconfigurable acoustic environments that have real-world properties. Further, although many psychoacoustic studies focus on lower-order perception, it cannot be forgotten that Soldier activities occur in the context of stress and fatigue, and that these can have an altering or intensifying effect on perception. Realistic accounting for these effects is one of the biggest challenges of ART's research.

4.1.1 Auditory Localization on the Battlefield

Auditory localization is another key component of ASA for the dismounted Soldier. Auditory localization ability can be used to develop a spatial map of the Soldier's surroundings, and those surroundings may or may not be familiar to the Soldier. Especially in complex urban settings, environmental sounds can alert a Soldier to activities in that environment—activities that may be visually obstructed by buildings, crowds of people, or other intervening structures. At the same time, ASA can be compromised by features of the urban environment; the cues used to spatially locate sounds can be significantly altered and even removed by the physical structures in the environment. Further, the PPE required for Soldier survivability, such as helmets and body armor, change the spectral characteristics of sounds as they travel to the Soldier's ears. HPDs and Tactical Communication and Protective Systems (TCAPS) also alter localization information and distance cues. For example, the safety controls of TCAPS use peak clipping and/or compression that alter binaural-level cues and have been reported to affect both the perceived location of the sound source and the perceived distance. Therefore, Soldiers relying on auditory information in order to better understand their operational environment must either adapt to these changes or find themselves at a potential operational disadvantage.

In parallel to auditory localization research, ARL auditory researchers are working to develop a model of auditory spatial perception that will allow us to predict the effects of changes to the HRTF on auditory localization ability. While there are a number of binaural models (see MacDonald, 2008, for examples), very few use all of the cues used by humans or perform in quite the same way. The basis of the ARL localization model is computationally simple, and the model predicts with a great deal of accuracy the location of a sound in azimuth relative to the head (MacDonald, 2005; MacDonald, 2008; MacDonald and Tran, 2006). In a recent ARL Director's Research Initiative, this model was extended to include models of the outer and middle ears, the cochlear basilar membrane, and the hair cell function (developed by Glasberg and Moore, 2002; Patterson et al., 1995; and Meddis, 1986, respectively). The model was recently applied to answer the question of how a Soldier localizes sound sources when two different short sounds arrive synchronously from different directions (Henry and MacDonald, 2009). Unlike most studies conducted in a laboratory, sounds in real-world environments do not

necessarily occur serially; they often occur simultaneously. The Dome Room of the EAR was used to present sounds simultaneously and to measure the ability of listeners to accurately estimate the location of a cued sound (Henry and MacDonald, 2009). These data were used to extend the sound localization model but have yet to be successfully implemented for helmet wear. There are still inconsistencies between the model's predictions and human performance data. Therefore, further research is planned for EAR, involving the collection of HRTF measurements and localization performance data for multiple sound source environments in order to improve the model's accuracy.

4.1.2 Auditory Motion Perception

Although the majority of ART's research has focused on stationary sounds, there has also been some work on moving sound sources. The study of moving sounds has a number of technical challenges. To some extent, motion can be simulated using panning algorithms and by presenting a sound successively from a spatially distributed array of loudspeakers like the ones housed in the EAR's Dome Room (see appendix A). To the extent that movement across an array of loudspeakers is perceived similarly to real movement, many questions can be answered using such a setup. The Dome Room was built with a provision to add a rotating loudspeaker simulating the actual movement of a sound source. This feature was not implemented because of budget limitations; however, the EAR manager hopes to add this capability to the EAR in the future. The planned upgrade will allow research studies comparing simulated sound motion to actual motion.

When sound source motion is simulated, spatial panning algorithms will be used. The spatial resolution of vector-based amplitude panning algorithms, the distances between loudspeakers, the spectral content of the sound sources, and the speed of motion will be investigated to find the minimal and optimal parameters for simulation of real sound sources moving through a varying environment. Factors to be studied include the directivity patterns, the auditory source width, the spectral content of the sound sources, etc. A veridical simulation of auditory motion will enable the realistic representation of battlefield sources moving over large distances.

4.1.3 Auditory Distance and Depth Perception

Direct estimation of distance is of relevance to Soldiers who need to call in coordinates for targeting or monitoring or to know their distance to an area of interest. This is a difficult task both visually and auditorily. A large number of studies in distance estimation have been reported in the literature; however, the distances of importance to Soldiers differ significantly from that used in most laboratory research. The distance estimation data reported in the literature are based on sound sources located either within near-field ranges of peri-personal space or within a distance up to about 10 m in an enclosed space (e.g., Bronkhorst and Houtgast, 1999; Loomis et al., 1999; Zahorik et al., 2005). In military environments, the distances of interest extend from 10 to 1000 m or even farther. In previous outdoor distance estimation studies conducted at ARL, sound sources were placed in 25- to 800-m distances from the listeners. The listener responses

differed greatly depending on the type of sound used (e.g., throat clearing, car horn, water splash), but in general, the listener underestimated distances that were <200 m and were unreliable in their estimation of greater distances. The interpretation of these data requires consideration of the varying environmental conditions (e.g., wind strength and direction) that greatly affect listeners' responses. Therefore, to separate environmental effects from the auditory capabilities of the listener and from the effects of various types of headgear, a number of distance estimation studies are being conducted and planned for the Distance Hall and OpenEAR (see appendix A). The Distance Hall allows the study of real distances up to 25 m and simulated distances without any reasonable limits. For example, a study is being currently set up in the Distance Hall to test differences in distance and depth perception with two related sound sources presented simultaneously or in short succession (e.g., two people talking, two guns firing).

The adjacent natural environment of the OpenEAR more than quadruples the distance of the Distance Hall, giving the researchers the opportunity to study distance and depth perception on a scale that is more relevant to the Soldier. As previously mentioned, perception of distance in an open space is affected by a multitude of factors affecting both the sound itself and the Soldier. Further, the perception of relative depth is now being affected by use of the newer TCAPS-style communications and hearing protection devices that provide hearing restoration and increased gain of ambient noises. In order to protect Soldier hearing, these devices limit the intensity level presented to the Soldier's ears by means of compression algorithms, limiters, and/or shut-off triggers. This alters the relative level cues used for distance estimation. As of the date of this publication, there is very little information about their effect on auditory spatial perception and overall performance. There are survey data that suggest that compression makes near sounds seem farther away and far sounds seem closer (Scharine et al., 2005). Other studies have shown left-right mislocalizations that may be the result of a loud noise triggering a shut-off in the near ear but not the far ear, making the sound louder in the far ear (Casali et al., 2011). However, to date these effects have not been systematically studied.

In terms of human factors, it is desirable to avoid altered spatial perception. However, it is possible that Soldiers can adapt to these distortions if sufficient spatial cues remain to allow remapping of the altered cues. To better understand this, ART intends to study the time course of adaptation and learning of localization and distance cues. Listeners are able to adapt to altered cues if they are linear transformations of the original cues (Shinn-Cunningham, 2000). The brain learns to interpret the monaural spectral changes caused by a listener's pinnae. With experience, a listener can adapt to altered pinnae (Hofman et al., 1998). Therefore, there is reason to believe that users of TCAPS systems may be able to adapt and compensate for distorted spatial information. Therefore, the planned new research will provide data that determine the extent of initial distortion, the time-course of adaptation, and the level of performance once adapted. The object is to provide the developers of TCAPS devices with information about which compression algorithms are most effective and to provide information for those training Soldiers in the use of TCAPS about the adaptation time needed for optimal SA.

4.1.4 Sound Identification on the Battlefield

Military operational environments are very rich in continuous and intermittent sound events, and the Soldiers need to identify their sources in order to make decisions about how to respond to those sounds. Reported studies have shown that the cues used for sound identification vary greatly depending on the context in which sounds occur. The Soldier gradually learns to identify sounds by recognizing those sound features that differentiate important sounds in the environment. However, the relevance of a set of features may vary greatly across different operational environments. For example, the character of a sound can be changed by wind, ground reflections, and attenuation as it travels through the air. The perception of this sound can be influenced by context, prior knowledge, and expectations. Changes to both the sound's character and the listener's perceptual "set" can affect sound identification. In turn, identification of a sound can affect the perception by informing the listener of the probabilities associated with potential perceptual interpretations, such as probable spatial location. For example, the estimation of auditory distance can be greatly affected by wind, ground reflections, expectations, and prior knowledge of the sound source. More importantly, sound character can be dramatically changed by the surrounding environment. A distant rifle shot in a jungle may sound like a stone's splash when it is thrown into a pond. Likewise, identification of a sound may affect the perceived location of that sound.

Recent sound recognition work, conducted in the Listening Laboratory of the EAR facility, focused on listener recognition of small-arms fire (e.g., Fluitt et al., 2010; Gaston and Letowski, 2010). This focus will expand to include the interaction of recognition with localization for a range of weapon-related sound sources. Gunfire is an example of a highly variable sound; changes to the observer-shooter relationship can create large differences in the temporal distribution of the impulse peaks for a particular firing event. Further, because these peaks contain both relevant and irrelevant localization cues, sound source localization is difficult. For supersonic bullets, there are two dominant sounds. The first is the ballistic crack caused by the bullet breaking the sound barrier, and the second is the muzzle blast caused by the explosive release of hot gases from the weapon barrel. The sound of the supersonic bullet propagates outward from the target line and arrives to the observer at an angle that is a function of the bullet's speed. The arrival time to the observer then is the addition of the time it takes the supersonic bullet to reach the point of outward propagation from the target line, plus the time it takes the ballistic crack to propagate (at the speed of sound) from the target to the observer. In contrast, the sound of the muzzle blast travels at the speed of sound along a direct path from the weapon barrel to the observer. As a consequence, the perceived relative timing of the ballistic crack and muzzle blast sounds depends greatly on the distance of the observer from both the weapon barrel and the bullet target line. In addition, localization based on the ballistic crack would correspond to the origin of the sound and thus some point in the direction of the bullet's target. Localization based on the muzzle blast would correspond to some point in the direction of the weapon's barrel.

ART's future work in the recognition and identification of small-arms fire will address the perceptual consequences of these acoustical realities. The Distance Hall of EAR was designed to facilitate the simulated movement of an approaching sound source, such as the travel of a bullet flying overhead or movement of a car toward the listener. By simulating the muzzle blast pathway and the ballistic crack, the ability to localize weapon fire can be investigated. Further, localization performance can be compared to that measure for an outdoor environment such as the M-Range or OpenEAR.

4.2 Adverse Listening Conditions

4.2.1 Noise

Noise is a recurrent component of ART's research because Soldiers are routinely exposed to unsafe levels of noise. Some of these noise sources are predictable and others, like improvised explosive device (IED) blasts, are unforewarned. Therefore, noise is included as a variable in auditory spatial studies with PPE and HPDs as factors affecting ASA. It also drives hearing protection and communication headsets. Recently ART researchers began working with West Point cadets in testing a nonlinear hearing protector developed at West Point. The tests were conducted in the Dome Room in a noisy environment with levels up to 115 dB in order to determine the threshold of the nonlinear behavior of the earplug.

4.2.2 Urban Terrain

An important variable included in many of ART's studies is urban terrain features that make auditory spatial orientation difficult (Scharine and Letowski, 2005; Scharine et al., 2009). The urban environment contains physical structures that obstruct vision and alter the sound pathway because of the reflection of sounds and noises from walls and buildings. In many traditional studies of auditory localization, the degradation of localization cues caused by reverberation has been avoided by conducting the experiment in an anechoic or near anechoic environment. Further, most of the localization studies were conducted in environments that were absent of visual cues. Obviously these environments are very different from those experienced by Soldiers. For example, the Soldiers in dismounted exercises at Fort Benning's Military Operations in Urban Terrain site were reporting difficulties with spatial orientation regardless of their state of hearing or vision. The question to be asked is whether the reported perception of degraded ASA is due to increased lack of visual cues or increased degradation of auditory spatial cues.

ART's interest in the simulation of complex acoustical environments was a major factor in the design of EAR and making it easily adaptable. Movable reflective walls have been placed in the Dome Room and the Distance Hall in order to create the reverberant environments needed to study the effects of reverberation on localization and movement perception. In addition, the Sphere Room has been instrumented to measure HRTFs in a simulated reverberant environment, and reflective panels are currently used in the Distance Hall in a study intended to determine the

effect of reflections and vision on auditory distance estimation. EAR was designed so that an urban environment could be simulated by combining the OpenEAR, Distance Hall, and Dome Room. By placing both the listener and the sound source inside the EAR or outdoors in the OpenEAR, or by placing one of them in the OpenEAR and the other in the EAR, the effect of a sound source's pathway, direct or indirect, can be studied. By locating the listener indoors facing the acoustic scene in the OpenEAR through an open large door, it is also possible to separate to some degree the effects of weather conditions on sound propagation and on the human observer. Future studies are planned to study the effects of indirect sound pathways on Soldier situation awareness either by creating simulated environments in the Sphere Room or by using sounds entering the Distance Hall from the Dome Room and OpenEAR.

4.3 Hearing Protection

4.3.1 Nonlinear Systems

Soldiers need to be protected from impulsive noise, such as the Soldier's own weapon fire, friendly fire, and enemy rifle and artillery sounds, and yet still be aware of their ambient environment. Traditional HPDs reduce sensitivity to the ambient auditory environment. Nonlinear (level-dependent) earplug-based HPDs that provide very little attenuation in quiet and in low-level noise but effectively close the ear against high-level impulse noises can allow ASA and still protect against unsafe noise levels. Such devices can be inexpensive and work well for impulse noises; however, they do not attenuate high-level continuous noises, such as vehicle noise. For that reason, they are sometimes combined with an additional switch-selectable protection against continuous noise. The successful use of such devices depends on accessibility (e.g., by a hand in a glove) and reliability of the switching device. Additionally, operation of the switch should not affect the fit and comfort of the earplug. These requirements create serious ergonomic and acoustic issues that have not yet been successfully solved and are one of the topics of the ARL-HRED ongoing research program.

4.3.2 Tactical Communication and Protection Systems (TCAPS)

The relatively new TCAPS with "talk through" hearing restoration can provide user-controlled amplification of ambient sounds and are an alternative to "switchable" nonlinear HPDs. For some Soldiers, the TCAPS offer the potential of "enhanced" hearing or superhearing beyond that of their normal capabilities. For Soldiers that have already experienced hearing loss, TCAPS can be regarded as "combat hearing aids"[*] because they can restore some of the lost sensitivity to sounds and allow hearing-disabled Soldiers to continue to serve. However, the methods used to amplify ambient levels vary widely and can result in dramatic alterations of some sound cues, especially those important for localization and distance estimation. As a result, although these systems represent a potential increase in capabilities, the net benefit to the Soldier is not well

[*]The term "Combat Hearing Aids" was used by Major Jillyen Curry-Mathis at a recent 2011 National Hearing Conservation Association workshop on Army Hearing Conservation.

understood and represents a necessary research area that focuses on understanding the changes in sound information caused by these devices and their resulting impact on performance. Therefore, ART's researchers are currently developing a set of studies using the Distance Hall and the OpenEAR environments to measure the effects of TCAPS devices on distance and depth perception. Stimulus levels will be chosen to test the effects of the compression and peak-limiting mechanisms on both speech communication and distance estimation and depth perception. After initial testing, repeated measurements will be made over the course of several days until asymptotic performance is reached. At that time, distance perception will be tested for both the aided and unaided states to measure the time course of adaptation to the TCAPS and its effect on overall spatial perception. This research will be combined with measurements of HRTFs in the Sphere Room and modeling efforts.

4.4 Speech Communication

Effective speech communication, especially in multitalker environments, is another critical element of Soldier performance. For example, the Army's Tactical Operation Centers (TOCs) are vehicle-, tent-, or room-based transitional centers of operations where several talkers may be engaged in related or unrelated person-to-person, telephone, or radio communications in the presence of other people and background noise (e.g., noise from power generators). There are very few known rules describing how to set up such TOCs to allow maximum intelligibility of parallel conversations and how to assure that all the people in the TOC have sufficient ASA and well perform their assigned tasks. When the EAR was being designed, the Listening Laboratory was created for research that could answer these and related questions. It has adaptive acoustics through absorptive panels that can be added to or removed from individual walls, up to 12 channels of simulated parallel telephone/radio communications, and up to 14 channels of loudspeaker-based simulated talkers. The laboratory's audio capabilities also permit simulation of various multichannel sound reproduction systems, which are compatible with sound systems from the Institute for Creative Technology—the Army-funded institute leading the Army's efforts in creating immersive environments for training and mission rehearsal purposes. In addition, this facility is designed for use in earphone-based auditory studies in which several listeners participate at the same time.

4.5 Optimized User Interfaces

A Soldier must be able to react quickly to a changing environment. In order to do so, he needs to be trained so that common tasks are automatic. In the heat of battle or the chaos following an IED explosion, his attention should be on variable factors in his environment rather than on his equipment or gear. Therefore, the role of proper sensory experience that can be preloaded and enhanced by proper sensory training and multisensory mission rehearsals cannot be underestimated. Further, the Soldier should be thoroughly acquainted with his hearing protection; its use should be automatic. The Soldier is also an element of the larger Army network and needs to be connected to the network through various means. One of the important

elements of this network is radio communication networking that shares attention resources with ASA and yet may impair ASA. A radio communication interface needs to interface easily with HPDs and allow both inter- and intra-squad communication and communication with higher echelons. To decrease the dependence of communication ability on hearing and the type of hearing protection, various unconventional communication interfaces may be used, including bone conduction (BC) and head-mounted tactile (HMT) interfaces. While BC research has been conducted at ARL-HRED for some time, still very little is known about tactile sensitivity of the head, the HMT interfaces are in their infancy, and their advantages and potential disadvantages need to be studied. The main consideration should be that the head-worn devices should be multifunctional and their design should have the least possible impact on ASA. Therefore, ART's researchers look for an optimal tradeoff between equipment functionality, Soldier's protection, and Soldier's sensory impairment.

5. ARL-HRED's Auditory Research Program

As discussed previously, much of ARL's auditory research is oriented toward spatial perception and ASA; features of the Soldier's environment and equipment such as helmets, hearing protection, and communications are factors that affect the ASA of the dismounted warrior. The auditory issues that are the focus of ARL-HRED's efforts have been addressed previously. Some spatial perception issues driven by current Soldier needs that have been investigated to date include the study of the effects of helmets and communications and hearing protection systems (C&HPS/TCAPS)* on auditory localization ability and if these effects can be predicted from changes to the HRTF.

A number of studies that examine the effects of helmets on auditory localization ability have been conducted. One of the more notable studies was conducted for the Vice Chief of Staff of the Army by the Infantry School in which ARL showed that the Advanced Combat Helmet (ACH) provides better localization ability as compared with the previously fielded Personnel Armor System for Ground Troops (PASGT) helmet. In another study, Scharine (2009) showed that ear coverage is a significant factor with respect to auditory localization ability, increasing the number of large localization errors (>25°) by 38% with respect to no ear coverage. This effect gets larger in reverberant environments. Different helmet shapes change auditory localization ability by altering the spectral shape of the sound wave arriving at the ear, which can negatively affect localization ability (Scharine et al., 2009; Scharine and Letowski, submitted to *Human Factors*). A similar effect has been measured for C&HPS/TCAPS (Scharine, 2005) and winter gear (Henry and Foots, 2011). In the latter study, ASA as measured by auditory

*The ART studies have commonly referred to communications and hearing protection systems as C&HPS. However, currently there exists a draft military standard for Tactical Communications and Protective Systems—TCAPS. The two acronyms are included here to enable cross-referencing.

localization accuracy in the horizontal plane is not affected through the use of a knit cap but can be negatively impacted through the wearing of a hooded jacket even when the signal is continuous.

An important element of ARL-HRED research efforts is to tie Soldier auditory abilities to Soldier performance and mission requirements. This is where it becomes important for research not be too reductionist in nature and where modeling can potentially provide a useful solution. It is a trivial but very important statement that the Soldier's environment is complex. While it is helpful to understand that PPE use alters and degrades ASA, especially localization ability, the following questions must be examined in the Soldier's context:

- Does loss of sensory capability due to equipment become unimportant when other factors like vision and reverberation are considered?
- What happens when attentional resources are overtasked?
- How can we lessen the effects of sensory narrowing?
- Does optimization of sensory ability significantly reduce cognitive load, or does it become less relevant overall?

If a model can be constructed that accounts for the physical and physiological processes that occur in the identification or localization of a sound, these data can be used in a number of ways. For example, Soldier Systems developers of new equipment would find such models useful tools for evaluation. More importantly, if incorporated into other Soldier performance models like the Infantry Warrior Simulation* (IWARS), they would allow the measurement of the effects of Soldier systems and acoustic environments on ASA. However, such models need to be approached carefully. Modeling the effects of acoustic variables like the effect of reverberation and indirect sound pathways requires that we are able to simulate these effects in a controlled laboratory setting. EAR's Sphere Room provides this capability, allowing capture of individual HRTFs and baseline localization performance under anechoic conditions and then the simulation of real-world acoustical effects in the same physical space, including but not limited to the effects of helmets, reverberation, noise, multiple sounds, and motion. Further, it allows direct comparisons between real acoustic environments and synthetic simulations using the same types and spatial arrangement of sound sources. This unique capability of the EAR is intended to help develop signal-processing techniques that result in more realistic and better-controlled Soldier immersion in virtual environments.

As addressed previously, another specific goal of auditory perception research at ARL-HRED is to improve Soldier performance by providing the Army with human factors requirements for the

*IWARS is a constructive force-on-force model for assessing the combat worth of systems and subsystems for both individuals and small unit dismounted warfighters in high-resolution combat operations. See https://files.pbworks.com/download/CKUUqYTInw/orsagouge/13331213/IWARS.pdf (accessed 27 February 2012).

key technologies necessary to assure supremacy in future land warfare. Therefore, an essential component of ART's long-term research plan includes looking at how spatial auditory capabilities tie into the overall abilities of a Soldier. This requires identifying and agreeing on representative Soldier tasks that require ASA and then manipulating Soldier auditory abilities in such a way that one can measure their effects on mission success. To some extent the research community still does not understand what in these situations baseline or benchmark capabilities are. Therefore, the future ART's research activities must determine the minimal required ASA for specific tasks (i.e., clearing buildings, determining locations of snipers, coordinating squad members). Even though the Soldier's environment is unpredictable and chaotic, research needs to be done in a controlled way in order to ensure that hearing capabilities are the cause of measured differences in performance. The EAR enables simulations of complex auditory environments so that Soldiers can be immersed in realistic soundscapes. Thereby, the Soldiers' abilities to detect, discriminate, localize, and track can be accurately measured in a controlled environment and subsequently retested in real scenarios of OpenEAR and performance ranges. A list of most of the recent, current, and developing studies conducted by the ARL-HRED in the EAR facility is included as appendix B.

6. Transitions and Plans

Auditory researchers at ARL collaborate with a number of other organizations in academia, industry, and the DOD. For example, in working on the issue of bone conduction, ART has collaborated with researchers at Embry-Riddle Aeronautical University (ERAU), North Carolina Agricultural and Technological State University (NCA&TSU), as well as companies such as Sensory Devices and TEMCO. ART researchers have ongoing collaborations with Missouri University of Science and Technology, working on the development of an immersive audio environment for Soldier combat training, and with the Natick Soldier Research, Development, and Engineering Center (NSRDEC), working on acoustic properties of headgear.

As documented previously, ART's role is to serve as a source of DOD information and research data for all normal-hearing related issues affecting the dismounted Soldier. As such, ART collaborates with DOD medical institutions, such as the Army's Public Health Command, USAARL, and WRNMMC, on issues related to hearing protection and hearing loss. In addition, ART researchers participate in the DOD-wide working groups on auditory research and hearing conservation. An example of such cooperation is the memorandum of agreement between ARL-HRED (ART), AFRL, and USAARL, formalizing data exchange and joint research among these three laboratories. In addition, ARL facilities operated by ART and ART researchers' expertise are shared with ARL's neighbor the Aberdeen Test Center in studies characterizing and recording vehicle and weapon noise. This association has provided ART researchers with access to military equipment that they do not normally have in-house.

The expertise of ART members is widely sought after; they serve as peer-reviewers for professional journals and active participants on American National Standards Institute, International Standards Organization, and International Electrotechnical Committee working groups, seeking to provide input on the best way to measure and regulate sound and devices used by Army personnel and researchers.

As an Army laboratory that conducts primarily basic research, ARL ensures that ART's research has currency and value to the DOD community by forming partnerships with other organizations through Technology Program Annexes, Army Technology Objectives (ATOs), and other formal and informal agreements. Much of the research on the effects of helmets and hearing protection has occurred in cooperation with NSRDEC. Auditory researchers at ARL play active roles as auditory consultants on integrated product teams that develop headgear for the Army, such as Future Force Warrior, Land Warrior, Dismounted Battle Command System, and the Ground Soldier System. Currently ART researchers are participating on the Helmet Electronics and Display System-Upgradeable Protection ATO, serving as auditory experts and testers of prototype headsets.

The multidisciplinary and multifaceted nature of ART research has been reflected in articles and paper summaries published in a wide range of journals. Some of the journals reporting ART's research studies include *Human Factors, Applied Acoustics*, *International Journal of Audiology*, *Ear and Hearing*, *Archives of Acoustics*, *Military Psychology*, *Journal of the Acoustical Society of America*, *Journal of Military and Strategic Studies*, *International Journal of Vibration*, *and Canadian Acoustics.* Members of the auditory research team contributed to nine chapters of the recently published book *Helmet-Mounted Displays: Sensation, Perception and Cognition Issues*. Similarly, ART researchers participated in recent years a number of academic and industry conferences, including those organized by the Acoustical Society of America, International Congress on Sound and Vibration, Human Factors and Ergonomics Society, Psychonomics, National Hearing Conservation Association, American Audiological Society, American Academy of Audiology (AudiologyNOW), and Joint Defense/Veterans Audiology Conference. A list of 2009–2011 ARL-HRED ART publications is included as appendix C. In addition, ART members teach courses at Morgan State University, Towson University, NCA&TSU, and other institutions, and serve as student advisors. ART also provides research opportunities to young people considering their career in science and technology through the Science and Engineering Apprenticeship Program high school program and its college component, the College Qualified Leaders program. ART's researchers are also regular contributors to the Great Explorations in Math and Science program, intended to increase interest of young people in science and technology.

ART's current research plans are aligned with the results and ongoing modernization of the ARL Sensory Performance program research. In this major research program, ART research occurs in conjunction with cognitive research and seeks to answer what happens between initial sensations, to perceptual interpretation, higher-order cognitive processes, and finally action. For

example, the ART's plans include a development, together with the Army Research Office, of the Multidisciplinary University Research Initiatives in Auditory Spatial Perception and Auditory Stealth expanding ART's collaboration with academia in solving some of more complex auditory performance problems for the Army.

7. References

Bronkhorst, A.; Houtgast, T. Auditory Distance Perception in Rooms. *Letters to Nature* **1999**, *397*, 517–520.

Casali, J. G.; Keady, J. P.; Killion, M. C.; Talcott, K. *Military Hearing Protection-Enhancement Devices (HPEDs): Protective, But Can the Soldier Locate the Shooter?* National Hearing Conservation Association: Mesa, AZ, 2011.

Fluitt, K.; Gaston, J.; Letowski, T.; Karna, V. *Feasibility of Audio Training for Identification of Auditory Signatures of Small Arms Weapons Fire*; ARL-TR-5413; U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, 2010.

Gaston, J. R.; Letowski, T. R. A Three-Stage Approach to Understanding Listener Perception of Weapon Signature for Small Arms. *Proceedings of NoiseCon*, 2010; Vol. 220, pp 1442–1454.

Glasberg, B. R.; Moore, B. C. J. A Model of Loudness Applicable to Time-Varying Sounds. *Journal of the Audio Engineering Society* **2002**, *50*, 331–342.

Henry, P. P.; MacDonald, J. A. *Development of a Model of Multisource Sound Localization*; ARL-TR-5223; U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, June 2010.

Henry, P.; Foots, A. Auditory Localization While Wearing Fleece Caps and Hooded Jackets. Poster presentation at *AudiologyNOW! 2011 Annual Convention for the American Academy of Audiology*, Chicago, IL, April 2011.

Hofman, P. M.; van Riswick, J. G. A.; van Opstal, A. J. Relearning Sound Localization With New Ears. *Nature Neuroscience* **1998**, *1*, 417–421.

Loomis, J. M.; Klatzky, R. L.; Golledge, R. G. Auditory Distance Perception in Real, Virtual, and Mixed Environments. In *Mixed Reality: Merging Real and Virtual Worlds*; Ohta, Y., Tamura, H., Eds.; Springer-Verlag: Secaucus, NJ, 1999; pp 201–214.

MacDonald, J. A. *An Algorithm for the Accurate Localization of Sounds.* Paper presented at the New Directions for Improving Audio Effectiveness, Neuilly-sur-Seine, France, 2005.

MacDonald, J. A. A Localization Algorithm Based on Head-Related Transfer Functions. *J. Acoust. Soc. Am.* **2008**, *123*, 4290–4296.

MacDonald, J. A.; Tran, P. K. A Sound Localization Algorithm for Use in Unmanned Vehicles. Paper presented at the 2006 AAAI Symposium on Aurally Informed Performance, 2006.

Meddis, R. Simulation of Mechanical to Neural Transduction in the Auditory Receptor. *J. Acoust. Soc. Am.* **1986**, *79*, 702–711.

Patterson, R. D.; Allerhand, M. H.; Giguere, C. Time-Domain Modeling of Peripheral Auditory Processing: A Modular Architecture and a Software Platform. *J. Acoust. Soc. Am.* **1995**, *98*, 1890–1894.

Scharine, A. A. *An Evaluation of Localization Ability With Selected Level-Dependent Hearing Protection Systems: A Field Study Conducted for the Future Force Warrior Integrated Headgear Integrated Process Team*; ARL-TR-3474; U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, 2005.

Scharine, A. *Degradation of Auditory Localization Performance Due to Helmet Ear Coverage: the Effects of Normal Acoustic Reverberation*; ARL-TR-4879; U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, 2009.

Scharine, A.; Letowski, T. R. *Factors Affecting Auditory Localization and Situational Awareness in the Urban Battlefield*; ARL-TR-3474; U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, 2005.

Scharine, A. A.; Mermagen, T. Characterization of the Environment for Auditory Research (EAR) at the U.S. Army Research Laboratory. *Proceedings of the 15th International Congress on Sound and Vibration*, DaeJeon, Korea, 6–10 July 2008.

Scharine, A.; Letowski, T. R. The Effect of Helmet Form on Sound Detection and Localization, submitted to *Human Factors*.

Scharine, A. A.; Henry, P. P.; Binseel, M. S. *An Evaluation of Selected Communications Assemblies and Hearing Protection Systems: A Field Study Conducted for the Future Force Warrior Integrated Headgear Integrated Process Team*; ARL-TR-3475; U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, 2005.

Scharine, A. A.; Fluitt, K.; Letowski, T. R. The Effects of Helmet Shape on Directional Attenuation of Sound. Paper presented at the Sixteenth International Congress on Sound and Vibration 2009, Krakow, Poland, 5–8 July 2009a.

Scharine, A. A.; Letowski, T. R.; Sampson, J. B. Auditory Situation Awareness in Urban Operations. *J. Military Strategic Studies* **2009b**, *11*, 1–28.

Shinn-Cunningham, B. G. Adapting to Remapped Auditory Localization Cues: A Decision-Theory Model. *Perception and Psychophysics* **2000**, *62*, 33–47.

Zahorik, P.; Brungart, D. S.; Bronkhorst, A. Auditory Distance Perception in Humans: A Summary of Past and Present Research. *Acta Acustica* **2005**, *91*, 409–420.

Appendix A. Environment for Auditory Research: Description and Operational Capabilities

A.1 Introduction

The Environment for Auditory Research (EAR) is a new U.S. Army research laboratory dedicated to spatial perception and speech communication research. The facility, designed by U.S. Army Research Laboratory (ARL) researchers Bruce Amrein and Tomasz Letowski, became operational in 2010. The EAR is a state-of-the-art and flexible research facility with the range of testing conditions extending from the stringent laboratory conditions to realistic operational conditions simulating field testing and battlefield activities. The general view of the EAR is shown in figure A-1. The facility consists of two basic elements: ClosedEAR and OpenEAR. The ClosedEAR (figure A-2) comprises four indoor research spaces (Sphere Room, Dome Room, Distance Hall, and Listening Laboratory) and one common control center (Control Room) that permits concurrent execution of three independent studies in various spaces. OpenEAR is an outdoor research space designed to represent a set of natural outdoor conditions allowing immediate comparison of data collected under stringent ClosedEAR conditions with the data representing realistic operational environments. The technical capabilities of OpenEAR are controlled together with technical capabilities of all indoor research spaces from the ClosedEAR's Control Room. Such arrangement permits the use of both the ClosedEAR and OpenEAR in the same study when needed. This capability is very important in research involving simulated urban environments.

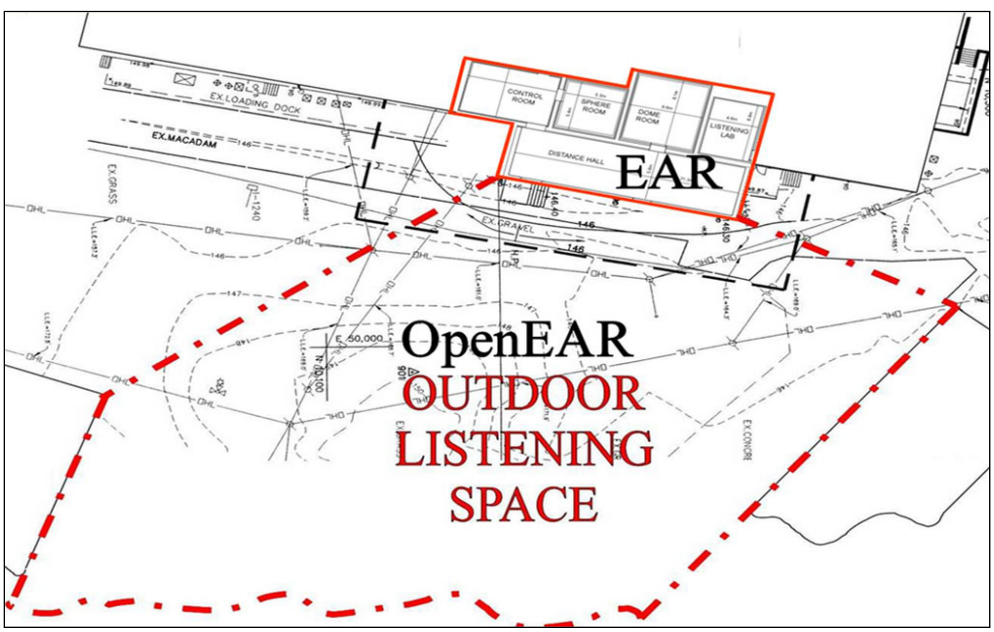

Figure A-1. Configuration of the Environment for Auditory Research (EAR).

ROOM DIMENSIONS	NORTH-SOUTH	EAST-WEST	HEIGHT
CONTROL ROOM	8.4 m	5.7 m	3.0 m
DISTANCE HALL	21.3 m	5.8 m	3.7 m
DOME ROOM	6.6 m	8.1 m	4.1 m
LISTENING LAB	4.6 m	6.4 m	3.5 m
SPHERE ROOM	5.3 m	5.4 m	4.9 m

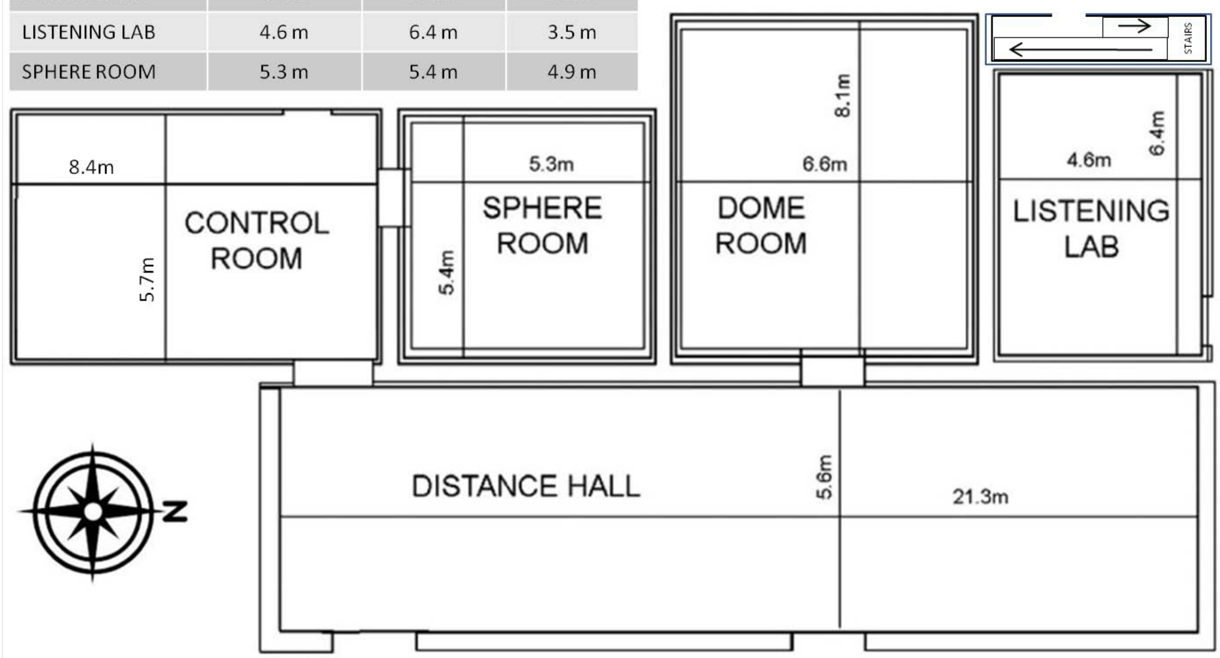

Figure A-2. Schematic configuration of interior spaces.

All the indoor research spaces comply with Noise Criterion-15 (NC-15), resulting in background noise levels below or close to the hearing threshold of young, otologically normal people. The spaces also have widely adjustable lighting and temperature conditions, permitting simulation of various operational conditions. The predominantly anechoic environment of the EAR can be modified, if needed, by using the internal and external elements to represent more realistic environments offering various acoustic test environments ranging from anechoic, through various simulated indoor conditions, to real field environments.

A.2 Functional Capabilities of the EAR

The research activities to be performed in the EAR that were the foundation of the design process for each EAR research space are listed in table A-1, and the associated technical requirements can be found elsewhere.[1] Some activities may have multiple forms or tasks, and in such cases they may be listed for more than one space. In addition, the EAR has three major operational capabilities that were critical in the EAR design but which are not captured in table A-1. First, in all five spaces the effects of various headgear (helmets, hearing protectors, etc.)

[1]Letowski, T.; Amrein, B.; Ericson, M. Environment for Auditory Research: Design Principles and Capabilities. *Proceedings of the 17th International Congress on Sound and Vibration*, Cairo, Egypt, 2010.

Table A-1. EAR spaces and main intended research activities.

Sphere Room	Dome Room	Distance Hall	Listening Lab	OpenEAR
Spatial orientation Situation awareness Global environment changes tracking Head-Related-Transfer-Function studies Stealth operation studies Auditory virtual reality	Sound source localization in horizontal and vertical plane Sound source tracking in horizontal and vertical plane (one or many sources) Directional sound detection Directional sound masking studies	Distance perception Depth perception Overfly perception Toward/away movement tracking Perceived sound source velocity studies Situation awareness	Sound reproduction system optimization studies Speech recognition Effects of room acoustics on speech intelligibility (adaptive acoustics) Multitalker and small space effects studies Earphone-based perception studies (parallel listening)	Spatial orientation Spatial masking Environmental effects studies Long-range acoustic communication studies

can be assessed under any of the principal research tasks. Second, many of the research activities conducted in the ClosedEAR may be replicated under more realistic conditions in the OpenEAR. Third, some of the activities can be conducted using two or more spaces and additional movable elements (e.g., simulation of urban environments).

A.3 Facility Description

A.3.1 Control Room

The Control Room (54 m^2 of floor area) is an integrated control center permitting complete and independent control of instrumentation and research activities in all four indoor spaces and an outdoor listening space. It contains the front end of all instrumentation and stimuli generation systems. The audio system of the EAR is powered by four computers and includes extensive automatic switching capability. The system is capable of generating up to 8 independent audio signals (64 signals in the sphere room) and transmitting them to any or all (~600) loudspeaker and earphone locations throughout the facility.

Functionality of the Control Room enables control and monitoring of as many as four (three indoors and one outdoors) simultaneous experiments conducted in various spaces of the facility from a single location. The networking capabilities of the EAR allow the control functions of the control room to be accessed from each test space, allowing a researcher to set up an experiment from within a target space. In addition, audio and video capabilities of the Control Room can be used to provide audio-video demonstrations and instructions for new users, experiment participants, and visitors. The view of one research control station in the Control Room is shown in figure A-3.

Figure A-3. The EAR Control Room.

A.3.2 Sphere Room

The Sphere Room is a 140-m^3 (5.3 × 5.4 × 4.9 m) auditory virtual reality space designed to investigate the integrity of auditory virtual spaces, realism of complex auditory simulations, effects of Head-Related Transfer Function on auditory perception, and effect of helmets and other headgear on spatial orientation in a three-dimensional dynamically changing environment (figure A-4, left). The sound reproduction system of the room consists of 57 loudspeakers distributed on a sphere and radially separated by about 25°.

A.3.3 Dome Room

The Dome Room is a 220-m^3 (6.6 × 8.1 × 4.1 m) space designed to study the human's ability to localize real or virtual, single or multiple, and stationary or moving sources in a horizontal plane or along two vertical arcs extending from –20° to +40° regarding listener's head position (figure A-4, right). The sound system capabilities support 2° horizontal and 10° vertical spatial resolution.

Figure A-4. Sphere Room (left) and Dome Room (right).

A.3.4 Distance Hall

The Distance Hall is a 440-m^3 (21.3 × 5.6 × 3.7 m) acoustically treated space designed to study auditory distance estimation and the effects of sound source movement toward and away from the listener on sound source detection and identification (figure A-5, left). Acoustic configuration and audio capabilities of the distance hall permit extensive investigation of localization and tracking of sound sources moving in a predetermined manner toward and away from the listener, auditory distance and depth estimation, tracking of sound sources moving above the listener, or detection and recognition of sound sources appearing far away from the listener.

A.3.5 Listening Laboratory

The Listening Laboratory is a unique multipurpose 140-m^3 (4.6 × 6.4 × 3.5 m) room for studying the effects of space acoustics (removable acoustic wall treatment) and sound source configurations on sound perception (figure A-5, right).

Figure A-5. Distance Hall (left) and Listening Laboratory (right).

A.3.6 OpenEAR

OpenEAR (figure A-6) is a 4459-m^2 outdoor extension of the EAR complex designed to replicate studies conducted in the laboratory environment in a natural field environment with the same listeners at almost the same time to reduce data uncertainty resulting from laboratory and field studies, which are conducted at different times and with different listeners.

Figure A-6. The view of OpenEAR through one of the Distance Hall's doors.

A.4 Basic Acoustic Conditions of the EAR

After completion of the EAR, the technical properties of the facility were evaluated following the guidelines of the relevant American National Standards Institute (ANSI) standard.[2] The tests included measurements of the reverberation time (RT), spatial character of sound decay, ambient noise levels with and without air conditioning/heating systems running, and noise reduction through walls. Some technical details of the EAR constriction can be found in the EAR documentation and in certain EAR-related publications.[1,3]

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[2]ANSI/ASA S12.2-2008. *American National Standard Criteria for Evaluating Room Noise,* American National Standard Institute, Melville, NY, 2008.

[3]Scharine, A.; Mermagen, T. Characterization of the Environment for Auditory Research (EAR) at the U.S. Army Research Laboratory. *Proceedings of the 15th International Congress on Sound and Vibration,* Daejon, Korea, 6–10 July 2008; pp 1842–1849.

A.4.1 Reverberation Time

RT of all ClosedEAR test spaces was measured with a 01-dB Symphonie system using dBBATI32 building acoustics software. The RT measurements were taken at the center of each test space and at the south end of the Distance Hall (expected listener location). The calculated RTs for octave frequency bands from 125 to 8000 Hz are shown in table A-2.

Table A-2. Reverberation time (RT) measured with the octave bands of noise.

Reverberation Time (s)	**Condition**	**Octave Band Frequency**						
		125 Hz	**250 Hz**	**500 Hz**	**1 kHz**	**2kHz**	**4 kHz**	**8 kHz**
Sphere Room	—	0.20	0.20	0.05	0.05	0.03	0.01	0.01
Dome Room	—	0.31	0.18	0.05	0.04	0.02	0.02	0.02
Distance Hall	C	0.35	0.42	0.40	0.09	0.05	0.03	0.02
Distance Hall	SE	0.35	0.41	0.40	0.06	0.05	0.03	0.02
Listening Laboratory	F	0.37	0.20	0.10	0.09	0.04	0.02	0.02
Listening Laboratory	NF	0.45	0.43	0.42	0.42	0.44	0.44	0.41

Notes: C = center of the room, SE = south end of the room, F = absorptive panels on the walls, NF = no absorptive panels. The short RT values for Sphere Room, Dome Room, and Listening Laboratory are good for sound localization and virtual reality studies. The RT of about 0.4 s at low frequencies in the Distance Hall is important for distance estimation and situation awareness studies because 0.4 s is generally accepted as a minimum RT required for congruent space rendering.

A.4.2 Early Room Reflections

Early reflection from the space boundaries can be very detrimental to spatial research because it can mislead the listener regarding the real position of the sound source or can even be heard as a separate sound—the echo of the original sound. Scharine and Mermagen[3] investigated the strength and delays of the early reflections in all EAR test spaces (Listening Laboratory with absorptive panels on the walls and Sphere Room without foam panels on the floor) and concluded that they are negligible in all of the rooms. Almost all early reflections were below –30 dB with respect to the level of the original sound and arrived between 7 to 25 ms after the direct sound. These reflections were caused by the floor and the metal structures supporting the arrays of loudspeakers. The strongest early reflection was observed in the center of the distance hall with the level of –22 dB and delay of 7 ms with respect to the direct sound. This reflection was most likely caused by a pair of doors facing each other in the middle of the distance hall (see figure A-2). Some buildup of broadband reverberation that began at 40 ms and fell below immeasurable levels at 60 ms was also observed in the distance hall. In addition, a weak single reflection from the far (north) wall at –70 dB was observed at 81.5 ms when both the microphone and the loudspeaker were located at the opposite (south) end of the hall. Two examples of typical reflections observed in the Dome Room and Distance Hall are shown in figure A-7.

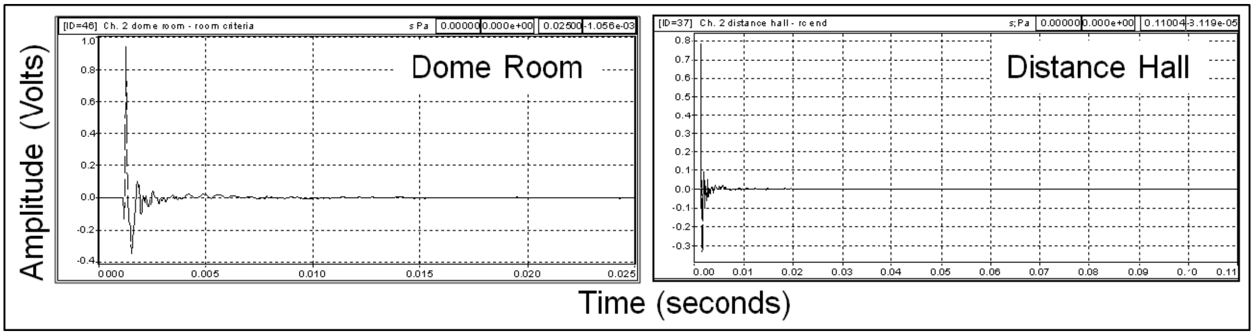

Figure A-7. Typical room reflections in Dome Room and Distance Hall (note different timescale).

A.4.3 Spatial Sound Decay

The sound pressure level produced by a sound source in an open space decreases at the rate of 6 dB per doubling of distance from the sound source (inverse square law). In the indoor situation, however, the sound energy becomes reflected from space boundaries affecting the distribution of sound pressure levels in the space. Therefore, the classical test to determine whether the sound field in a closed space has free sound field properties is the measurement of the rate of sound pressure decay with increasing distance from the sound source. As space boundaries become more absorptive and as the size of the space increases, the indoor sound field more closely resembles the free field existing in an open space. In order for the EAR spaces to simulate open hemi-anechoic space conditions, the sound pressure at the listener's locations should be close to that predicted by the inverse square law.[4] Thus, to determine the extent to which hemi-anechoic listening conditions are met in the EAR spaces, the sound pressure levels at various distances from the sound source were measured in the individual spaces. An example of sound pressure level changes of a pink noise signal measured at 1, 2, 3, and 4 m away from a loudspeaker in the Dome Room is shown in table A-3. Data for one-third octave-band noises are also available, and they support hemi-anechoic field conditions in the Dome Room down to 200 Hz. Similar data sets exist for various distances in the Distance Hall and Listening Laboratory spaces and for the fixed loudspeaker to listener distance in the sphere room.

Table A-3. Sound pressure levels of a pink noise signal measured in the dome room at various distances from the sound source.

Sound Pressure Level (dB)	**Distance From the Sound Source (m)**			
	1	**2**	**3**	**4**
Dome Room	94.8	89.2	85.0	84.2

Note: The normal operational distance from the loudspeaker to the listener in the Dome Room is 3 m.

[4]ISO/DIS 26101. *Acoustics – Test Methods for the Qualification of Free-Field Environments*; International Organization for Standardization: Geneva, Switzerland, 2010.

A.4.4 Ambient Noise Levels

Ambient noise levels measured in the EAR spaces are listed in table A-4. The levels shown in the table were measured in the center of the space with air conditioning and heating systems turned off. When these systems are operational, they slightly increase noise levels at low and medium frequencies, resulting in the overall increase of the noise level by 1–2 dB A-weighted. During the measurements, the fan of the system was always on. The measurements were made with a type I sound level meter from CEL Instruments Ltd., model number 573.C1.

Table A-4. Octave-band sound pressure levels for Noise Criterion NC-15[2] and ANSI S3.1-1999[5] and the actual ambient noise levels measured in all ClosedEAR (dB A - overall A-weighted level).

Sound Pressure Level (dB)	**Octave Band Frequency**								
	63 Hz	**125 Hz**	**250 Hz**	**500 Hz**	**1 kHz**	**2kHz**	**4 kHz**	**8 kHz**	**dB A**
NC-15	47.0	36.0	29.0	22.0	17.0	14.0	12.0	11.0	—
ANSI S3.1-1999	—	29.0	21.0	16.0	13.0	14.0	11.0	14.0	—
Air Conditioning and Heating Systems Off (Fan On)									
Sphere Room	34.1	27.4	17.3	12.2	11.2	12.4	12.4	12.9	18.9
Dome Room	32.3	22.9	11.9	10.3	9.8	9.8	10.8	13.8	18.8
Distance Hall	37.2	27.9	20.2	14.9	10.3	11.9	11.0	10.3	20.7
Listening Laboratory	35.0	26.2	14.8	12.2	9.8	9.8	10.6	11.6	18.9
Operational Conditions Without Loudspeaker Monitoring									
Control Room	47.5	44.2	52.4	48.9	49.3	46.4	36.4	25.9	53.1

A.4.5 Acoustic Isolation

Noise reduction (NR) levels of all internal and external walls of the EAR were measured using a pink noise signal and an omnidirectional (dodecahedral) loudspeaker (CESVA FP120 Sound Source) placed at 1 m from a specific wall. The level of the signal measured at 1 m from the loudspeaker (parallel to the wall) was 106 dB SPL (100 dB A) ±1 dB. The noise transmitted to the other room was measured at 1 m from the wall across from the loudspeaker and, additionally, in the sphere room, at the location of the listener. In the case of the wall separating the two largest spaces (Dome Room and Distance Hall), the measurements were made at three separate locations along the wall with location no. 2 directly across the door separating both spaces. All measurements were made with the CEL 573.C1 sound level meter.

NR values for the most critical EAR partitions are shown in figure A-8 and table A-5. The values have met or exceeded projected levels and provide required operational conditions for two or more concurrent experiments to be run in the EAR. The only exception is concurrently conducting two separate experiments in the dome room and distance hall spaces.

[5]ANSI/ASA S3.1-1999 (R2008). *American National Standard Criteria for Maximum Permissible Ambient Noise Levels for Audiometric Test Rooms*; American National Standard Institute: Melville, NY, 2008.

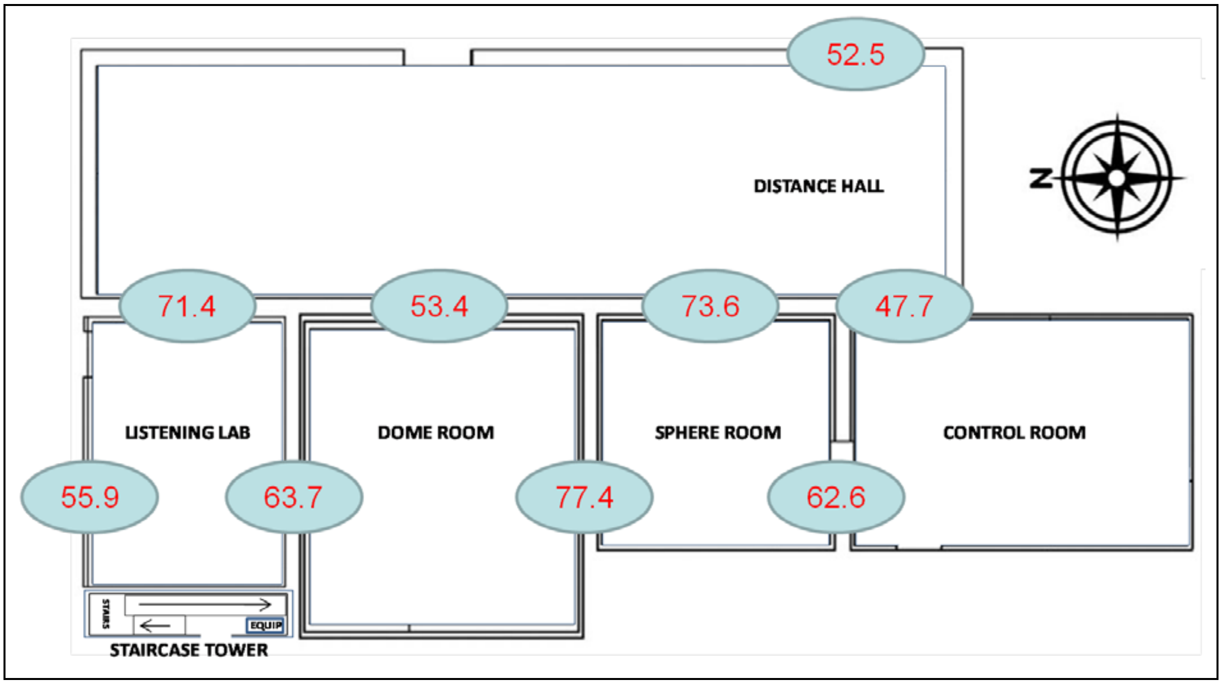

Figure A-8. NR data (dB [A-weighted]) for walls between various test spaces of the EAR and walls separating EAR from the OpenEAR and the other parts of the building. Air-conditioning and heating systems were off; ventilation fan was on.

Table A-5. NR data for walls between various test spaces of the ClosedEAR and walls separating ClosedEAR from the OpenEAR and the other parts of the building. Air-conditioning and heating systems were off; ventilation fan was on.

Wall	Octave Band Frequency								
	63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2kHz	4 kHz	8 kHz	dB A
1 CR - DH 3	25.3	46.3	48.2	47.0	46.3	49.7	51.4	>75	47.7
2 CR - SR	38.4	51.0	60.8	66.8	71.2	73.2	>75	>75	62.6
3 DR - SR	48.6	70.6	74.3	>80	>80	>80	>75	>75	77.4
4 SR - DH 3	42.3	61.7	70.0	72.0	>80	>80	>75	>75	73.6
5a DR 1 - DH 1	35.5	52.4	54.6	63.7	70.2	67.8	64.6	>75	57.7
5b DR 2 - DH 2	32.6	51.0	49.8	55.6	60.5	61.1	60.0	>75	53.4
5c DR 3 - DH 3	42.3	55.5	60.9	67.4	72.4	64.8	65.8	>75	62.2
6 LL - DR	35.9	50.0	63.1	>80	>80	>80	>75	>75	63.7
7 LL - DH 1	52.2	58.2	69.9	>80	>80	>80	>75	>75	71.4
8 Hallway - LL	35.6	44.6	51.6	67.4	74.0	78.4	79.7	>75	55.9
9 OpenEAR - DH 3	31.1	43.4	50.9	58.5	62.3	62.8	63.8	>70	52.5

However, such possibility was not included in the design because of door arrangements and safety issues. The Dome Room, Distance Hall, and OpenEAR have been specifically designed to be included together in a single experiment that simulates an urban environment.

A.5 Summary

The ARL EAR is a unique and powerful research tool with indoor and outdoor capabilities that are unmatched at any current military, academic, or industrial facility. The goal of the design was to create exceptionally quiet indoor research spaces meeting NC-15 standards. In all conditions, including fully operational heating and air-conditioning systems, this standard was met, except at 6 and 8 kHz in some of the spaces. At those frequencies, all rooms had ambient noise levels approximately 1–3 dB above the criteria levels, which was determined as acceptable. The ANSI requirements for the maximum permissible ambient noise level for ears not covered[5] was met in all of the indoor research spaces in all conditions.

None of the EAR spaces were designed to be truly anechoic. The goal of the EAR design was to achieve reverberation times of ~0.2 s (0.4 s in the distance hall) or less at frequencies above 300 Hz in order to reduce the impact of reverberation on speech and spatial perception while facilitating relatively natural listening conditions. Such reverberation time was also a compromise resulting from the need for a sturdy floor structure necessary for supporting reconfigurable add-on acoustic elements. This criterion was met in all chambers at and above 250 Hz, and the reverberation times in all indoor research spaces were <0.1 s at 1 kHz, greatly outperforming the design requirements.

The EAR facility is used by ARL researchers to increase our understanding of Soldier auditory capabilities and the sound-related challenges the Soldier faces on the modern battlefield. However, the EAR is also open to external researchers to conduct a joint or their own research in the fields of interest to the U.S. Army. The selected list of such topics includes spatial orientation, distance and depth estimation, virtual displays design, signature detection and identification, icons and warning signals design, and perception of moving sound sources.

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Appendix B. Most Recent and Current Auditory Studies Conducted in the Environment for Auditory Research Facility

This appendix appears in its original form, without editorial change.

Project Name	Status	Point of Contact	Facility
Auditory recognition of the direction of walking	The 17th International Congress on Sound & Vibration (2010); paper	LTC Marjorie Grantham	Dome Room
A three-stage approach to understanding listener perception of weapon signature for small arms.	The 2010 NOISE-CON; paper	Jeremy Gaston	Listening Laboratory
Evaluation of auditory characteristics of communications and hearing protection systems (C&HPSs): Part II - Speech intelligibility	ARL-TR-5075	Paula Henry	Dome Room
Evaluation of auditory characteristics of communications and hearing protection systems (C&HPS): Part III – Auditory localization	Data collection completed; ARL Technical Report (in preparation)	Paula Henry	Dome Room
Development of a model of multisource sound localization	ARL-TR-5223	Paula Henry	Dome Room
Feasibility of audio training for identification of auditory signatures of small arms fire	ARL-TR-5413	Kim Fluitt	Listening Laboratory
Auditory awareness while wearing fleece caps and hooded jackets	Poster at 2011 AudiologyNOW!	Paula Henry	Dome Room
The effects of spatial visual information and head motion cues on auditory spatial judgments.	Acoustical Society Conference May 2011; poster	Mark Ericson	Distance Hall and OpenEAR
Comparison of user volume control settings for personal music players with three earphone configurations in quiet and noisy environments.	Journal Submission (in Press) Journal of the American Academy of Audiology	Paula Henry	Dome Room

Minimum audible movement angle measured for a straight trajectory with and without reverberation	Journal submission (in preparation)	Paula Henry	Distance Hall
Determining the optimal linear loudspeaker spacing for simulated motion	Protocol approved; ongoing data collection	Mark Ericson	Distance Hall
Sound Localization response time and accuracy data for free-field and MOUT conditions. Part 1: Baseline data and validation of virtual presentation techniques.	Data collection complete, data analysis underway	Angelique Scharine	Sphere Room
Sound Localization response time and accuracy data for free-field and MOUT conditions. Part II: Reverberation.	Protocol approved. Currently working on presentation techniques.	Angelique Scharine	Sphere Room
Auditory depth and distance perception of simultaneous and non-simultaneous sound sources	Protocol approved; data collection to begin soon ;	Kim Fluitt	Distance Hall and OpenEAR
The effects of auditory and visual spatial cues on depth judgments	Paper presented at 131st Audio Engineering Society Convention, 2011.	Mark Ericson	Distance Hall

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Appendix C. List of Publications and Posters of the Auditory Research Team (2009–2011)

This appendix appears in its original form, without editorial change.

2011

Amrein, B.E. & Letowski ,T. (2011). Predicting and ameliorating the effect of very intense sounds on the ear: The Auditory Hazard Assessment Algorithm for Humans (AHAAH). *Proceedings of the Human Factors & Medicine Panel HFM-207 Symposium (RTO-MP-HFM-207)*. Halifax (Canada): NATO.

Amrein, B.E. & Letowski, T. (2011). The big bang dilemma: Is weapon effectiveness the greatest friend of Soldiers' hearing safety? *Proceedings of the Forum Acusticum 2011*, Aalborg (Denmark): EAA.

Kalb, J.T. (2011). Modeling the reduction of impulse noise hazard by hearing protectors. *Proceedings of the Forum Acusticum 2011*, Aalborg (Denmark): EAA.

McBride, M., Tran, P., Letowski, T., & Patrick, R. (2011). The effect of bone conduction microphone locations on speech intelligibility and sound quality. *The Journal of Applied Ergonomics*, 42, 495-502.

Blue-Terry, M. & Letowski, T. (2011). The effects of various white noise levels on the Callsign Acquisition Test (CAT) and Modified Rhyme Test (MRT) scores for conversational speech level. *Ergonomics*, 54 (2): 139-145.

Pollard, K.A. (2011). Making the most of alarm signals: the adaptive value of individual discrimination in an alarm context. *Behavioral Ecology* 22 (1), 93-100.

Pollard, K.A., & Blumstein, D.T. (2011). Social group size predicts the evolution of individuality. *Current Biology*, 21 (5), 413-417.

Abouchacra K, Besing J, Koehnke J,, & Letowski T. (2011). The effects of reverberation on a listener's ability to recognize target sentences in the presence of up to three synchronized masking sentences. *International Journal of Audiology*, 50 (7): 468-475.

Abouchacra, K.S., Koehnke, J., Besing, J., & Letowski, T. (2011). Sentence recognition in the presence of competing speech messages presented in the audiometric booths with reverberation time of 0.4 and 0.6 second. *Archives of Acoustics*, 36 (1): 3-14.

Henry, P. P. & Foots, A. (2011). Auditory localization while wearing fleece caps and hooded jackets. Poster presentation at *AudiologyNOW! 2011 Annual Convention for the American Academy of Audiology*, Chicago, IL, April 2011.

Norin, J., Emanuel, D., & Letowski, T. (2011). Speech intelligibility and nonlinear hearing protection devices. *Ear and Hearing*, 32 (5): 642-649.

Toll, L., Emanuel, D., & Letowski, T. (2011). Effect of static force on bone conduction hearing thresholds and comfort. *International Journal of Audiology*, 50 (9): 632-635.

Letowski, T. & Letowski, S. (2011). Localization error: Accuracy and precision of auditory localization. In: P. Strumillo (Ed.), *Advances in Sound Localization*, pp: 55-78. Rijeka (Croatia): InTech (ISBN: 978-953-307-224-1).

2010

Fluitt, K., Gaston, J., Letowski, T., & Karna, V. (2010). Feasibility of audio training for identification of auditory signatures of small arms weapons fire. Technical Report ARL-TR-5413. Aberdeen Proving Ground, MD: U.S. Army Research Laboratory.

Hairston, W.D., Letowski, T.R., & McDowell, K. (2010). Low-level auditory processing as predictive tool for within- and cross-modal performance. *Proceedings of the 27th Army Science Conference*. Orlando (FL): ASAALT.

Hairston, D., Letowski, T., & McDowell, K. (2010). Predictors of task-related modulation in the auditory brainstem response. Poster presented at the Society for Neuroscience Annual Meeting (Neuroscience 2010), San Diego (CA): 13-17 November.

Blue, M., Ntuen, C., & Letowski, T. (2010). Speech intelligibility measured with shortened versions of Callsign Acquisition Test. *Applied Ergonomics 41 (2),* 291-294.

Henry, P. P. & MacDonald, J. A.(2010). *Development of a Model of Multisource Sound Localization*; ARL-TR-5223; U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, June 2010.

Myles, K., & Kalb, J. T. (2010*). Guidelines for head tactile communication.* Technical Report ARL-TR-5116. Aberdeen Proving Ground, MD: U.S. Army Research Laboratory.

Myles, K. (2010). *Using nonverbal behaviors to detect threat in urban environments.* Technical Report ARL-TR-5102. Aberdeen Proving Ground, MD: U.S. Army Research Laboratory.

Henry, P. & Weatherless, R. (2010). *Evaluation of auditory characteristics of communications and hearing protection systems (C&HPSs) Part II- Speech intelligibility.* Technical Report ARL-TR-5075. Aberdeen Proving Ground, MD: U.S. Army Research Laboratory.

Henry, P. & Weatherless, R. (2010). *Evaluation of auditory characteristics of communications and hearing protection systems (C&HPSs) Part I - Sound attenuation to low intensity sounds.* Technical Report ARL-TR-5050. Aberdeen Proving Ground, MD: U.S. Army Research Laboratory.

Pollard, K.A., Blumstein, D.T., & Griffin, S.C. (2010). Pre-screening acoustic and other natural signatures for use in noninvasive individual identification. *Journal of Applied Ecology 47,* 1103-1009.

Price, G. R. (2010). *Critique of "An analysis of the blast overpressure study data comparing three exposure criteria" by Murphy, Khan and Shaw.* Technical Report ARL- CR-657. Aberdeen Proving Ground, MD: U.S. Army Research Laboratory.

Letowski, T., Amrein, B., & Ericson, M. (2010). Environment for Auditory Research: Design principles and capabilities. *Proceeding of the 17th International Congress on Sound and Vibration (ICSV).* Cairo (Egypt): IIAV.

Grantham, M., Gaston, J., & Letowski, T. (2010). Auditory recognition of the direction of walking. Proceeding of the 17th International Congress on Sound and Vibration (ICSV). Cairo (Egypt): IIAV.

Gaston, J., & Letowski, T. (2010). A three-stage approach to understanding listener perception of weapon signature for small arms. *Proceedings of the 2010 National Conference on Noise Control Engineering (NOISE-CON 2010), 220,* 1442-1454: Baltimore (MD): INCE.

Kalb, J. T. (2010). A hearing protector model for predicting impulsive noise hazard. *Proceedings of the 2010 National Conference on Noise Control Engineering (NOISE-CON 2010) 220*, 715-726. Baltimore (MD): INCE.

Abouchacra, K., Sinno, S., & Letowski, T. (2010). Three-dimensional audio interface: A user's survey. *Proceedings of the 2010 National Conference on Noise Control Engineering (NOISE-CON 2010) 220*, 612-623. Baltimore (MD): INCE.

Tran, P. & Letowski, T. (2010). Speech intelligibility of air conducted and bone conducted speech over radio transmission. *Proceedings of the 2010 National Conference on Noise Control Engineering (NOISE-CON 2010), 220,* 547-653. Baltimore (MD): INCE.

Price, G. R. (2010). Susceptibility to intense impulse noise: evidence from the Albuquerque dataset. *Proceedings of Meetings on Acoustics* POMA, 9, 1-21. (http://scitation.aip.org/POMA).

Patrick R., McBride M., Letowski T., & Tran P. (2010). Bone conduction intelligibility: headset comparison study. *Proceedings of the 2010 Industrial Engineering Research Conference*. Cancun (Mexico): IIE.

Hairston, D., Letowski, T., & McDowell, K. (2010). Within- and cross-modal modulation of the auditory brainstem response. Poster presented at the Cognitive Neuroscience Society Meeting 2010 Annual Meeting (CNS 2010), Montreal (Canada): April 17-20.

Scharine, A., Letowski, T., Mermagen, T., & Henry, P. (2010). Learning to detect and identify acoustic environments from reflected sound. *Military Psychology* 22: 24-40.

2009

Fasanya, B. & Letowski, T. (2009). Acceptable Noise Levels (ANLs) for Speech and Music for Young People with Normal Hearing. *Proceedings of the 7th Annual Meeting of the Society for Human Performance in Extreme Environments*. San Antonio (TX): SHPEE.

Gaston, J.G., Letowski, T., & Fluitt, K.F. (2009). Mapping listener perception of weapon signature for single-shot impulse sounds. Poster presented at the 9th Annual Auditory Perception, Cognition and Action Meeting (APCAM), Boston (MA): November 19.

Amrein, B. & Letowski, T. (2009). The Environment for Auditory Research. *Canadian Acoustics 37 (3)*, 152-153.

Scharine, A. A., Letowski, T. R., & Sampson, J. B. (2009). Auditory situation awareness in urban operations. *Journal of Military and Strategic Studies*, *11(4):* 1-28.

Henry, P., Amrein, B., & Ericson, M. (2009). *The Environment for Auditory Research.* Technical Report ARL-RP-283. Aberdeen Proving Ground, MD: U.S. Army Research Laboratory.

Abouchacra, K., Letowski, T., Koehnke, J., & Besing, J. (2009). Clinical application of the Synchronized Sentence Set (S^3). *Proceedings of the 16th International Congress on Sound and Vibration on CD (paper # 352*). Cracow (Poland): IISV.

Scharine, A., Fluitt, K., & Letowski, T. (2009). The effects of helmet shape on directional attenuation of sound. *Proceedings of the 16th International Congress on Sound and Vibration on CD (paper # 53*). Cracow (Poland): IISV.

McBride, M., Weatherless, R., Mermagen, T., & Letowski, T. (2009). Effects of hearing protection on speech communication. *Proceedings of the 16th International Congress on Sound and Vibration on CD (paper # 48*). Cracow (Poland): IISV.

Tran, P., Amrein, B. E., & Letowski, T. R. (2009). Audio helmet-mounted displays. In C. E. Rash, M. B. Russo, T. R. Letowski, & E. T. Schmeisser (Eds.), *Helmet-mounted displays: Sensation, perception and cognition issues* (pp. 175-236). Ft. Rucker, AL: U. S. Army Aeromedical Research Laboratory.

Maronrooge, S., Emanuel, D., & Letowski, T. (2009). Basic anatomy of the hearing system. In C. E. Rash, M. B. Russo, T. R. Letowski, & E. T. Schmeisser (Eds.), *Helmet-mounted displays: Sensation, perception and cognition issues* (pp. 279-306). Ft. Rucker, AL: U. S. Army Aeromedical Research Laboratory.

Emanuel, D., Maronrooge, S., & Letowski, T. (2009). Auditory function. In C. E. Rash, M. B. Russo, T. R. Letowski, and E. T. Schmeisser (Eds.), *Helmet-mounted displays: Sensation, perception and cognition issues* (pp. 307-334). Ft. Rucker, AL: U. S. Army Aeromedical Research Laboratory.

Scharine, A. A., Letowski, T. R., & Cave, K. (2009). Auditory perception and cognitive

performance. In C. E. Rash, M. B. Russo, T. R. Letowski, & E. T. Schmeisser (Eds.), *Helmet-mounted displays: Sensation, perception and cognition issues* (pp. 391-490). Ft. Rucker, AL: U. S. Army Aeromedical Research Laboratory.

Scharine, A. A., & Letowski, T. R. (2009). Auditory conflicts and illusions. In C. E. Rash, M. B. Russo, T. R. Letowski, & E. T. Schmeisser (Eds.), *Helmet-mounted displays: Sensation, perception and cognition issues* (pp. 579-598). Ft. Rucker, AL: U. S. Army Aeromedical Research Laboratory.

Ghirardelli, T. G., & Scharine, A. A. (2009). Auditory-visual interactions. In C. E. Rash, M. B. Russo, T. R. Letowski, & E. T. Schmeisser (Eds.), *Helmet-mounted displays: Sensation, perception and cognition issues* (pp. 599-618). Ft. Rucker, AL: U. S. Army Aeromedical Research Laboratory.

Melzer, J., Brozoski, F., Letowski, T., Harding, T., & Rash, C. (2009). Guidelines for HMD design. In C. E. Rash, M. B. Russo, T. R. Letowski, & E. T. Schmeisser (Eds.), *Helmet-mounted displays: Sensation, perception and cognition issues* (pp. 805-848). Ft. Rucker, AL: U. S. Army Aeromedical Research Laboratory.

Myles, K. P. & Binseel, M. S. (2009). Exploring the tactile modality for HMDs. In C. E. Rash, M. B. Russo, T. R. Letowski, & E. T. Schmeisser (Eds.), *Helmet-mounted displays: Sensation, perception and cognition issues* (pp. 849-876). Ft. Rucker, AL: U. S. Army Aeromedical Research Laboratory.

Binseel, M., Kalb, J., & Price, G. R. (2009). *Using the Auditory Hazard Analysis Algorithm for Humans (AHAAH) software, beta release W93e.* Technical Report ARL-TR-4987. Aberdeen Proving Ground, MD: U.S. Army Research Laboratory.

Scharine, A. A. (2009). *Degradation of auditory localization performance due to helmet ear coverage: The effects of normal acoustic reverberation.* Technical Report ARL-TR-4879. Aberdeen Proving Ground, MD: U.S. Army Research Laboratory.

Myles, K. & Kalb, J. T. (2009). *Vibrotactile sensitivity of the head.* Technical Report ARL-TR-4696. Aberdeen Proving Ground, MD: U.S. Army Research Laboratory.

Hairston, W.D., Letowski, T., & McDowell, K. (2009). Examining cross-modal influence of the auditory brainstem response. Poster presented at the 10th International Multisensory Research Forum. New York (NY): 29 June - 2 July.

Scharine, A. A., (2009). Predicting sound attention and identification: Modeling identification of category, subcategory and specific source as a function of mission context. Technical Report ARL-MR-730. Aberdeen Proving Ground, MD: U.S. Army Research Laboratory.

Tran, P. K., & Bujanda, A. (2009). *Universal hearing protection earplug for military application.* Technical Report ARL-MR-0716. Aberdeen Proving Ground, MD: U.S. Army Research Laboratory.

Fedele, P. D, & Dorney, A. L. (2009). *Analysis of fatigue influence on the performance of networked Joint Biological Point Detection Systems' operators.* Technical Report *ARL*-TN-368. Aberdeen Proving Ground, MD: U.S. Army Research Laboratory.

Henry, P., Amrein, B., & Ericson, M. (2009). The Environment for Auditory Research. *Acoustics Today, 5 (3),* 9-16.

Henry, P., Tran, P., & Letowski, T. (2009). *Comparison of bone conduction technologies.* Technical Report ARL-TR-4705. Aberdeen Proving Ground, MD: U.S. Army Research Laboratory.

Emanuel, D., & Letowski, T. (2009). *Hearing Science*. Baltimore (MD): Lippincott, Williams, and Wilkins.

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